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14. ABSTRACT

Fluid-structure interaction (FSI) is known to be one of the most challenging classes of problems in scientific computing. With creative methods for coupling the fluid and structure, we can increase the scope and efficiency of the FSI modeling. Multiscale methods, which now play an important role in computational mathematics, can also increase the accuracy and efficiency of the computer modeling techniques. The main objective of this project is to develop new multiscale methods specifically targeting FSI computations. Some of these methods are multiscale in

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Report Title

Final Report: Multiscale Space-Time Computational Methods for Fluid-Structure Interactions

ABSTRACT

Fluid-structure interaction (FSI) is known to be one of the most challenging classes of problems in scientific computing. With creative methods for coupling the fluid and structure, we can increase the scope and efficiency of the FSI modeling. Multiscale methods, which now play an important role in computational mathematics, can also increase the accuracy and efficiency of the computer modeling techniques. The main objective of this project is to develop new multiscale methods specifically targeting FSI computations. Some of these methods are multiscale in the way the time-integration technique is performed (i.e. temporally multiscale), some are multiscale in the way the spatial discretization is done (i.e. spatially multiscale), and some are in the context of the sequential-coupling techniques that we are developing in this project. The objectives of the project include determining the range of applicability of these multiscale and sequential-coupling techniques and generating an engineer's guide to multiscale FSI computations.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
08/12/2013	1.00	Bradley Henicke, Kenji Takizawa, Anthony Puntel, Nikolay Kostov, Tayfun E. Tezduyar. Space–time techniques for computational aerodynamics modeling of flapping wings of an actual locust, Computational Mechanics, (8 2012): 0. doi: 10.1007/s00466-012-0759-x
08/12/2013	6.00	Kenji Takizawa, Tayfun E. Tezduyar. Space–time computation techniques with continuous representation in time (ST-C), Computational Mechanics, (7 2013): 0. doi: 10.1007/s00466-013-0895-y
08/12/2013	5.00	Kenji Takizawa, Tayfun E. Tezduyar, Spenser McIntyre, Nikolay Kostov, Ryan Kolesar, Casey Habluetzel. Space–time VMS computation of wind-turbine rotor and tower aerodynamics, Computational Mechanics, (7 2013): 0. doi: 10.1007/s00466-013-0888-x
08/12/2013	4.00	Kenji Takizawa, Bradley Henicke, Anthony Puntel, Nikolay Kostov, Tayfun E. Tezduyar. Computer modeling techniques for flapping-wing aerodynamics of a locust, Computers & Fluids, (11 2012): 0. doi: 10.1016/j.compfluid.2012.11.008
08/12/2013	3.00	KENJI TAKIZAWA, DARREN MONTES, SPENSER MCINTYRE, TAYFUN E. TEZDUYAR. SPACE–TIME VMS METHODS FOR MODELING OF INCOMPRESSIBLE FLOWS AT HIGH REYNOLDS NUMBERS, Mathematical Models and Methods in Applied Sciences, (02 2013): 0. doi: 10.1142/S0218202513400022
08/12/2013	2.00	Kenji Takizawa, Nikolay Kostov, Anthony Puntel, Bradley Henicke, Tayfun E. Tezduyar. Space–time computational analysis of bio-inspired flapping-wing aerodynamics of a micro aerial vehicle, Computational Mechanics, (8 2012): 0. doi: 10.1007/s00466-012-0758-y
08/31/2014	9.00	Kenji.Takizawa, Bradley Henicke, Anthony Puntel, Nikolay Kostov, Tayfun E. Tezduyar. Computer Modeling Techniques for Flapping-Wing Aerodynamics of a Locust, Computers & Fluids, (10 2013): 125. doi:
08/31/2014	10.00	Kenji Takizawa , Tayfun E. Tezduyar , Spenser McIntyre , Nikolay Kostov , Ryan Kolesar , Casey Habluetzel. Space-Time VMS Computation of Wind-Turbine Rotor and Tower Aerodynamics, Computational Mechanics, (01 2014): 1. doi:
08/31/2014	11.00	Kenji Takizawa , Tayfun E. Tezduyar . Space-Time Computation Techniques with Continuous Representation in Time (ST-C), Computational Mechanics, (01 2014): 91. doi:
08/31/2014	12.00	Kenji Takizawa , Tayfun E. Tezduyar , Austin Buscher , Shohei Asada. Space-Time Interface-Tracking with Topology Change (ST-TC), Computational Mechanics, (10 2013): 0. doi:
08/31/2014	13.00	Tayfun E. Tezduyar, Nikolay Kostov, Kenji Takizawa. Sequentially-Coupled Space-Time FSI Analysis of Bio-inspired Flapping-Wing Aerodynamics of an MAV, Computational Mechanics, (08 2014): 213. doi:
08/31/2014	15.00	Kenji Takizawa , Tayfun E. Tezduyar , Ming-Chen Hsu , Nikolay Kostov , Spenser McIntyre, Yuri Bazilevs . Aerodynamic and FSI Analysis of Wind Turbines with the ALE-VMS and ST-VMS Methods, Archives of Computational Methods in Engineering, (05 2014): 0. doi:

08/31/2014 14.00 Kenji Takizawa , Yuri Bazilevs , Tayfun E. Tezduyar, Ming-Chen Hsu, Ole Oiseth , Kjell M. Mathisen , Nikolay Kostov, Spenser McIntyre. Engineering Analysis and Design with ALE-VMS and Space-Time Methods,
Archives of Computational Methods in Engineering, (05 2014): 0. doi:

08/31/2014 16.00 Kenji Takizawa , Tayfun E. Tezduyar. Main Aspects of the Space-Time Computational FSI Techniques and Examples of Challenging Problems Solved,
Mechanical Engineering Reviews, Japan Society of Mechanical Engineers, (01 2014): 1. doi:

09/13/2015 22.00 Kenji Takizawa, Yuri Bazilevs, Tayfun E. Tezduyar, Ming-Chen Hsu, Ole Øiseth, Kjell M. Mathisen, Nikolay Kostov, Spenser McIntyre. Engineering Analysis and Design with ALE-VMS and Space–Time Methods,
Archives of Computational Methods in Engineering, (05 2014): 481. doi: 10.1007/s11831-014-9113-0

09/13/2015 23.00 Yuri Bazilevs, Kenji Takizawa, Tayfun Tezduyar, Ming-Chen Hsu, Nikolay Kostov, Spenser Mcintyre. Aerodynamic and FSI Analysis of Wind Turbines with the ALE-VMS and ST-VMS Methods,
Archives of Computational Methods in Engineering, (12 2014): 359. doi:

09/13/2015 24.00 Kenji Takizawa, Tayfun E. Tezduyar, Ryan Kolesar, Cody Boswell, Taro Kanai, Kenneth Montel. Multiscale methods for gore curvature calculations from FSI modeling of spacecraft parachutes,
Computational Mechanics, (10 2014): 1461. doi: 10.1007/s00466-014-1069-2

09/13/2015 25.00 Tayfun E. Tezduyar, Austin Buscher, Kenji Takizawa. Space–time computational analysis of MAV flapping-wing aerodynamics with wing clapping,
Computational Mechanics, (01 2015): 1131. doi: 10.1007/s00466-014-1095-0

09/13/2015 26.00 Kenji Takizawa, Tayfun E. Tezduyar, Takashi Kuraishi. Multiscale space–time methods for thermo-fluid analysis of a ground vehicle and its tires,
Mathematical Models and Methods in Applied Sciences, (11 2015): 2227. doi: 10.1142 /S0218202515400072

09/13/2015 27.00 Franco Rispoli, Giovanni Delibra, Paolo Venturini, Alessandro Corsini, Rafael Saavedra, Tayfun E. Tezduyar. Particle tracking and particle–shock interaction in compressible-flow computations with the V-SGS stabilization and $$YZ\beta $$ Y Z ? shock-capturing,
Computational Mechanics, (05 2015): 1201. doi: 10.1007/s00466-015-1160-3

09/13/2015 28.00 Kenji Takizawa, Tayfun E. Tezduyar, Hiroki Mochizuki, Hitoshi Hattori, Sen Mei, Linqi Pan, Kenneth Montel. Space–time VMS method for flow computations with slip interfaces (ST-SI),
Mathematical Models and Methods in Applied Sciences, (11 2015): 2377. doi: 10.1142 /S0218202515400126

09/13/2015 21.00 Kenji Takizawa, Tayfun E. Tezduyar, Austin Buscher, Shohei Asada. Space–time interface-tracking with topology change (ST-TC),
Computational Mechanics, (10 2013): 0. doi: 10.1007/s00466-013-0935-7

TOTAL: **22**

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations:

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

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(d) Manuscripts

Received	Paper

TOTAL:

Number of Manuscripts:

Books

Received	Book

TOTAL:

Received	Book Chapter
08/31/2014 17.00	Kenji Takizawa, Yuri Bazilevs, Tayfun E. Tezduyar, Ming-Chen Hsu, Ole Oiseth, Kjell M. Mathisen, Nikolay Kostov, Spenser McIntyre. Computational Engineering Analysis and Design with ALE-VMS and ST Methods, Germany: Springer, (01 2014)
08/31/2014 18.00	Yuri Bazilevs, Kenji Takizawa, Tayfun E. Tezduyar, Ming-Chen Hsu, Nikolay Kostov, Spenser McIntyre. Computational Wind-Turbine Analysis with the ALE-VMS and ST-VMS Methods, Germany: Springer, (01 2014)

TOTAL: **2**

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Kenneth Montel	0.00	
Sen Mei	0.00	
Linqi Pan	0.00	
Ruochun Zhang	0.00	
FTE Equivalent:	**0.00**	
Total Number:	**4**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Tayfun Tezduyar	0.15	
FTE Equivalent:	**0.15**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: 0.00

Names of Personnel receiving masters degrees

NAME	
Kenneth Montel	
Total Number:	**1**

Names of personnel receiving PHDs

NAME
Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

Abstract
Fluid-structure interaction (FSI) is known to be one of the most challenging classes of problems in scientific computing. With creative methods for coupling the fluid and structure, we can increase the scope and efficiency of the FSI modeling. Multiscale methods, which now play an important role in computational mathematics, can also increase the accuracy and efficiency of the computer modeling techniques. The main objective of this project is to develop new multiscale methods specifically targeting FSI computations. Some of these methods are multiscale in the way the time-integration technique is performed (i.e. temporally multiscale), some are multiscale in the way the spatial discretization is done (i.e. spatially multiscale), and some are in the context of the sequential-coupling techniques that we are developing in this project. The objectives of the project include determining the range of applicability of these multiscale and sequential-coupling techniques and generating an engineer's guide to multiscale FSI computations.

Objective
Fluid-structure interaction (FSI) continues to be one of the most challenging classes of problems in scientific computing. Creative methods for coupling the fluid and structure parts are essential in increasing the scope and efficiency of FSI modeling. Multiscale methods will also continue to play an important role in computational mathematics and will increase the accuracy and efficiency of the computer modeling techniques. In multiscale computations, time-step size restrictions, imposed by numerical stability and accuracy considerations, pose a challenge. These restrictions depend on grid refinement, and also fluid and structure might have different time-step size requirements. Reducing the time-step size (or increasing the time-integration power) everywhere is the easiest way but not computationally efficient. Our objective is to develop new multiscale methods specifically targeting FSI computations. Some of these methods are multiscale in selecting the time-integration and time-step size (i.e. temporally multiscale), some are multiscale in selecting the grid refinement and interpolation power of the functions used (i.e. spatially multiscale), some in the way the small-scale flow behavior is represented in the computations, and some are in the context of the sequential-coupling techniques that we are developing in this project. Additionally, some of these methods take advantage of the space-time (ST) nature of our formulations, some use higher-order temporal basis functions in this context, and some can deal with the topology changes (TCs) in the flow domain, such as contact between solid surfaces, without compromising accurate representation of the flow patterns near solid surfaces. These methods can also be extended to thermo-fluid analysis, where the method is multiscale in the way the small-scale thermo-fluid behavior is represented and also spatially multiscale in the way a more accurate thermal solution is obtained with a global/local analysis. They can also be extended to computational analysis that can handle subdomains that contain spinning structures while maintaining an accurate representation of small-scale flow behavior near the surfaces of the spinning structure. With an added particle-tracking method, these methods can also be extended to computational analysis of erosion problems, where the small-scale flow behavior near the surfaces of the structure need to be accurately represented. Our objective includes determining the range of applicability of these multiscale and sequential-coupling techniques and generating an engineer's guide to multiscale FSI computations.

Approach
In the sequentially-coupled FSI approach, we first have a fully-coupled FSI computation with baseline spatial and temporal accuracy. The baseline grid refinement level, interpolation power of the finite element functions used, time-step size and the time-integration power determines that accuracy. Using the baseline structural deformation as given, we improve the spatial and temporal accuracy of the fluid mechanics part by carrying out fluid-only computations with better grid refinement, more interpolation power for the finite element functions, smaller time-step size and more time-integration power. In this way, we can, for example, compute the unsteady wake flow more accurately. Similarly, by using the baseline fluid mechanics forces at the fluid-structure interface as given, we can improve the spatial and temporal accuracy of the structural mechanics part by carrying out structure-only computations. In this way, we can, for example, compute the stress concentration at a given point more accurately. Although it will be more challenging, we also plan to use these multiscale spatial and temporal accuracy enhancements in the context of fully-coupled FSI computations. One of the ways to do that, for example, is to use, in the context of a fully-coupled FSI computation, more time-integration power in the fluid part or in certain zones of the fluid part. Increasing the time-integration power will increase the range of time-step sizes that can be used while maintaining the stability and accuracy of the computations. In general we propose to use, whenever it is needed or more efficient to do so, higher-order (NURBS) temporal basis functions in the ST context. Temporal NURBS basis functions can also be used in continuous representation of the solution, either from the already computed data or in the formulation used in computing the data. Our approach to multiscale FSI computations includes taking advantage of the ST nature of our methods in dealing problems involving TCs, including contact between solid surfaces, and but doing that in the context of the ST interface-tracking (moving-mesh) method, which enables accurate representation of the flow patterns near solid surfaces. Out approach in multiscale thermo-fluid analysis includes deriving the space-time variational multiscale (ST-VMS) method for the coupled fluid mechanics and thermal-transport problem. It also includes a global/local analysis that is spatially multiscale and can be used for more accurate computation of the thermal fluxes. In handling subdomains that contain spinning structures, our approach is to use the ST slip-interface (ST-SI) method that we are developing. The ST-SI method will properly account for the kinematic and flux conditions between the two sides of the SI. Our approach in multiscale particle tracking in erosion modeling is based on one-way dependence between the particle motion of the flow field.

Scientific Barriers

Data exchange in multiscale computations will be one of the main challenges, especially in the context of a fully-coupled FSI computation. Projecting solutions between grids with different refinement levels, especially from a coarse grid to a fine grid, is always challenging, and the way we address that challenge will quite often be problem-specific. Coupling between zones with different time-step sizes or different time-integration powers is another challenge that needs to be addressed. Sequentially-coupled FSI computing is rather intensive in I/O access and that needs be addressed in a parallel computing environment. The ST nature of our methods and using higher-order temporal basis functions create a computational paradigm change, which might require special iterative and parallel solution techniques suitable for the new paradigm. The ST-TC method in some cases might require carefully designed mesh moving strategies that might also be effort intensive. The ST-VMS derivation in the context of thermo-fluid analysis will involve many coupling terms and this might increase the cost of the computations.

Significance

Accurate and robust FSI modeling is key to a realistic simulation that takes into account the true nature of a challenging problem in computational science and engineering. Multiscale techniques, in general, give us more accuracy and efficiency. The sequential-coupling techniques, which will be limited to certain classes of FSI problems, gives us more computational efficiency and more flexibility. With that flexibility and a multiscale approach, we can increase the spatial and temporal accuracy of the results in an efficient way. With NURBS temporal basis functions, we can significantly improve the accuracy and efficiency of the temporal representation of the surface and mesh motion, remeshing, and the solution. Being able to deal with TCs in the ST context would open new doors in accurate computation of the problems involving such TCs, including contact between solid surfaces, as in the case of the aerodynamics of clapping wings. Being able to deal with multiscale thermo-fluid analysis will significantly extend the power of the ST-VMS method. Being able to deal with spinning structures while accurately representing the small-scale flow behavior will enable accurate simulation of a wide class of turbomachinery problems, including wind turbines. A reliable multiscale erosion model will enable to include in these simulations a predictive capability for structural erosion due to dust or rain. Multiscale and sequential-coupling FSI computer modeling techniques that can increase the accuracy and efficiency of the computations in a parallel-computing setting will help computational scientists and engineers bring solutions to complex, real-world problems, including those relevant to the US Army and the Department of Defense. We expect that the type of problems that will benefit from such powerful and practical FSI modeling techniques will include the flapping wing aerodynamics of Micro Air Vehicles (MAV), aerodynamics of Unmanned Air Vehicles (UAV), Micro-Electro-Mechanical Systems (MEMS), aerodynamics of rotors and turbines, aerodynamics of parachutes, and inflatable structures subjected to wind loads.

Accomplishments

Flapping-Wing MAV Aerodynamics with Sequential FSI Coupling

We have successfully applied the sequential FSI coupling technique to flapping-wing aerodynamics of an MAV. The wing structure is modeled with shell elements. The results are preliminary, and will be reported in a future publication.

New Element Length Defintion for the Diffusion-Dominated Limit in the ST-VMS Method

A new element length definition has been introduced [1] for the diffusion-dominated limit in conjunction with our variational multiscale ST (ST-VMS) method. This element length definition is used in two of the stabilization parameters. The new stabilization parameters give us a more robust method. Test computations with wind-turbine aerodynamics at actual scales and speeds [1] demonstrate the robustness of the method.

Successful Testing of Rotation Representation with Constant Angular Velocity Using NURBS

We have successfully tested [1] the method we have developed based on using temporal NURBS basis functions for rotation representation with constant angular velocity. Test computations with wind-turbine aerodynamics at actual scales and speeds [1] demonstrate how the path of the points on the rotor can be represented as perfect circles with constant angular velocity.

Successful Testing of Efficient Mesh Motion and Remeshing for Rotational Motions

We have successfully tested [1] using temporal NURBS basis functions for efficient mesh motion and remeshing for flow problems with rotating mechanical components. Test computations with wind-turbine and rotor aerodynamics at actual scales and speeds [1] demonstrate how we can move the mesh very efficiently and decrease the frequency of remeshing (a total of just 6 times).

ST Computation Techniques with Continuous Representation in Time

We have introduced ST computation techniques with continuous representation in time (ST-C), using temporal NURBS basis functions [2]. This gives us a temporally smooth, NURBS-based solution, which is desirable in some cases, and a more efficient way of dealing with the computed data. We introduced two versions of ST-C. In the first version, the smooth solution is extracted by projection from a solution computed with a different temporal representation, typically a discontinuous one. We use a successive projection technique with a small number of temporal NURBS basis functions at each projection, and therefore the

extraction can take place as the solution with discontinuous temporal representation is being computed, without storing a large amount of time-history data. This version is not limited to solutions computed with ST techniques. In the second version, the solution with continuous temporal representation is computed directly by using a small number of temporal NURBS basis functions in the variational formulation associated with each time step.

Sequentially-Coupled FSI (SCFSI) with Shell Elements
We have successfully completed the formulation, implementation and testing of the sequentially-coupled FSI (SCFSI) where the structure is modeled with shell elements. The shell elements are based on the Kirchhoff-Love shell model.

Bio-Inspired Flapping-Wing MAV Aerodynamics with the SCFSI
We have successfully completed the application of the SCFSI with shell and membrane elements to bio-inspired flapping-wing aerodynamics of an MAV. The wing motion and deformation data, whether prescribed fully or partially, is from an actual locust, extracted from high-speed, multi-camera video recordings of the locust in a wind tunnel. We use mainly our ST-VMS method for the flow computations. We also use the ST-SUPS method, which is the ST method based on the SUPG and PSPG stabilizations. These are supplemented with special ST techniques targeting flapping-wing aerodynamics, and the common feature for much of these special ST techniques is using NURBS basis functions in temporal representation. That includes temporal representation of the wing and mesh motion. Temporal representation with NURBS is also a key feature of the remeshing process.

SCFSI Analysis of Bio-Inspired Flapping-Wing Maneuvers and Modified Flapping of an MAV
In addition to the straight-flight case, we analyzed cases where the MAV body had rolling, pitching, or rolling and pitching motion, where we assumed that the MAV was somehow able to perform such maneuvers. We showed how these maneuvers influence the lift and thrust. We also studied the variations of the flapping patterns. In the first study, we altered the synchronization between the forewings (FWs) and hindwings (HWs) by advancing or delaying the FW motion relative to what it is in the original locust data. This allows us to seek an optimum point for the lift and thrust production and evaluate the possibility of using the variation in the synchronization to alter the flight performance. In the second study, we introduce asymmetry (across the sagittal plane) to the flapping. From a practical standpoint, it is unlikely to have asymmetric flapping in the MAV design, at least in the current ones. Still, it would be valuable to have the ability to study the effect of such asymmetry for the purpose of evaluating more complex MAV designs. We created a test case where the left and right wings are flapping still with the same frequency, but one side is delayed with respect to the other.

Space-Time Interface-Tracking with Topology Change (ST-TC)
We have successfully formulated and implemented an ST interface-tracking (moving-mesh) method that addresses the computational challenges associated with contact between moving solid surfaces and other cases of topology change (TC). This is a new version of the Deforming-Spatial-Domain/Stabilized Space-Time (DSD/SST) method, and we call it "ST-TC." The ST-VMS method is the core flow computation method. The ST-TC method includes a master-slave system that maintains the connectivity of the "parent" mesh when there is contact between the moving interfaces. It is an efficient, practical alternative to using unstructured ST meshes, but without giving up on the accurate representation of the interface or consistent representation of the interface motion. The ST-TC method has the interface-tracking accuracy, the TC flexibility, and the computational practicality.

ST-TC Computation of the Aerodynamics of Wing Clapping
Being able to compute the aerodynamics of wing clapping with an interface-tracking (moving-mesh) method gives us the accuracy needed to properly represent the flow details of the clapping. This will be important in making the aerodynamic analysis of the MAV wing flapping more reliable. The ST-TC method gives us that capability. We have successfully tested the ST-TC method in a 2D computation with a pair of symmetrically-flapping solid surfaces, with contact between those surfaces during the flapping.

ST-TC Computation of the Aerodynamics of Wing Clapping in 3D
We have successfully extended the ST-TC method to 3D computation of wing clapping. This required a very sophisticated mesh moving method.

Thermo-Fluid Analysis of a Ground Vehicle and its Tires
We have successfully demonstrated how the ST-VMS method we developed for multiscale thormo-fluid analysis with global/local analysis can be applied to thermo-fluid analysis of a ground vehicle and its tires

ST-SI Computational Analysis of a Vertical-Axis Wind Turbine
We have successfully demonstrated how the ST-SI method we developed for multiscale aerodynamic analysis with spinning structures can be applied to accurate aerodynamic analysis of a vertical-axis wind turbine.

Multiscale Compressible-Flow Computation with Particle Tracking
We have successfully tested the multiscale method we developed for particle-laden compressible flows in supersonic

computations.

Collaborations and Leveraged Funding

The FSI simulations we carried out for our NASA parachute project helped us to better understand the numerical challenges involved in fluid-structure coupling and multiscale computations. We collaborated with Dr. Yuri Bazilevs from University of California, San Diego, who is an expert in NURBS-based spatial interpolation. We also learned from our NSF project, which was on aerodynamic modeling of the flapping locust wings and which gave us a test platform for our multiscale ST techniques.

Conclusions

FSI modeling is now an important part of computational engineering and science, with a wide class of applications, including those very relevant to the Army and Department of Defense. We have formulated effective multiscale and sequential coupling techniques for FSI computations that, for certain classes of problems, will increase the efficiency without compromising the accuracy.

Stabilization parameters embedded in the VMS methods, including the ST-VMS method that we use, play an important role in the robustness and accuracy of the computations. While this might seem like a fine detail to many, it is in fact part of modern computing technologies. Taking advantage of the ST nature of our methods and using temporal NURBS basis functions open new doors for us. The SCFSI method where the structure is represented with shell elements gives us a new analysis and design capability, with the target application being the bio-inspired flapping-wing aerodynamics of MAVs. This includes being able to use designs where the wing motion and deformation data comes from an actual locust, with the data extracted accurately from high-speed, multi-camera recordings of the locust. The ST-TC method enables accurate computation of FSI problems with TCs, including contact between solid surfaces, as in the case of the aerodynamics of clapping wings of an MAV. Because the method is still an ST interface-tracking (moving-mesh) method, it can accurately represent the flow patterns and boundary layers near solid surfaces, such as the surfaces of clapping wings. The ST-VMS method we developed for thermo-fluid analysis and aerodynamic analysis with spinning structure will substantially extend the scope the multiscale methods.

We have the following specific conclusions.

A. The sequential FSI coupling technique to can successfully be applied to flapping-wing aerodynamics of an MAV.
B. The new element length definition for the diffusion-dominated limit in conjunction with the ST-VMS method increases the robustness and accuracy of the turbulent-flow computations.
C. With temporal NURBS basis functions, practical computations can be performed where path of the points on a rotating object need to be represented as perfect circles with constant angular velocity.
D. Mesh motion and remeshing can be handled in a very efficient way with temporal NURBS basis functions.

E. The SCFSI method where the structure is represented by shell elements can successfully be used in aerodynamic analysis and design of flapping wings of an MAV.
F. The analysis and design can be for wing motion and deformation patterns prescribed fully or partially from an actual locust,
G. The analysis and design can be for various forms of aerodynamic maneuvers, such as rolling, pitching, or rolling and pitching motion, and variations in the flapping patterns, such varying the synchronization between the FW and HW or introducing asymmetry between the left and right wings.
H. The ST-TC method has the interface-tracking accuracy, the TC flexibility, and the computational practicality. It enables FSI computations with accurate representation of the flow patterns near solid surfaces even when those surfaces come into contact.
I. The method has the potential to be applied to accurate computation of the aerodynamics of clapping wings.
J. The ST-VMS method for thermo-fluid analysis can successfully bring solution to this class of problems while accurately representing the small-scale flow and thermal transport.
K. The ST-SI method can successfully bring solution and analysis to flow problems with spinning structures while maintaining the accurate representation of the small-scale flow behavior near the spinning structure.

Technology Transfer

The computational technology of using temporal NURBS basis functions can be directly used in Army applications requiring aerodynamics or hydrodynamics computations with moving objects. While we tested and demonstrated these techniques in the context of a ST finite element formulation, they can also be used in different moving-mesh and remeshing contexts, such as ALE finite element or finite volume computations, which are probably more commonly used techniques by the Army research community. The method we introduced for continuous representation in time using temporal NURBS basis functions can also be directly used in Army applications requiring continuous representation of the computed data. The wing motion and deformation data used in the MAV flapping-wing computations and the aerodynamic data generated for various MAV maneuvers and flapping-pattern variations can be useful to the Army MAV designers. Accurate thermo-fluid analysis of ground vehicles and their tires can be a very useful analysis tool for the Army ground vehicles.

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